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Nutrient Recovery From Farm Ponds: Hydroponic Plant Production and Other Means

A Review

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CONTENTS

Page

Abstract 1

Introduction 1

Nutrient recovery from farm ponds 2

  Nutrient-uptake capabilities 2

    Nutrient-uptake kinetics 2

    Direct tests for competition 7

  Nutrient requirements for maximum growth 7

    Terrestrial angiosperms 7

    Phytoplankton 9

  External factors affecting nutrient uptake 10

  Utilization of aquatic weeds 12

  Monocultures 13

    Fish and other animals 13

    Algae 13

Summary and conclusions 13

  Hydroponic culture of plants 13

    Competition for nutrients 13

    Plant yields in dilute solution 14

  Other means of nutrient recovery 14

References 14

TABLES

1. Nutrients in natural waters 2
2. Phosphate phosphorus uptake kinetics 4
3. Sulfate sulfur uptake kinetics 5
4. Nitrate nitrogen uptake kinetics 5
5. Ammonium nitrogen uptake kinetics 5
6. Potassium uptake kinetics 6
7. Summary of nutrient-uptake kinetics 6
8. Nutrient concentrations required for plant growth in solution culture, by plant 8
9. Nutrient concentrations required for plant growth in solution culture, by nutrient 9
10. Effects of stirring or flow rate on nutrient uptake and growth 10
11. Possible uses for harvested aquatic weeds 12

Nutrient Recovery From Farm Ponds: Hydroponic Plant Production and Other Means

A Review

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ABSTRACT

This literature review considers primarily the potential for hydroponic culture of terrestrial plants in eutrophic farm ponds. The nutrient-absorbing capabilities of various plant species were compared by means of the half-saturation constant, K_m. Compared with most phytoplankton species, many terrestrial species seem to have an advantage for the uptake of potassium, would compete about equally for phosphate, and are at a disadvantage for the uptake of nitrate. Phosphate and nitrate are most likely to be limiting nutrients in farm ponds. Stirring and pH control would probably be needed for hydroponic culture. Terrestrial plants will not remove enough phosphorus from farm ponds to limit phytoplankton blooms. Also considered are the direct utilization of aquatic weeds and the use of monocultures such as fish (and other animals) and algae, but these methods have little potential as means of nutrient recovery. KEYWORDS: algae, farm ponds, fish, hydroponics, kinetics (Michaelis-Menten), literature reviews, nutrient recovery, nutrient solutions (plants), plankton, plant production (farm ponds), plants, weeds (aquatic).

INTRODUCTION

The 4 to 5 million farm ponds in the United States are generally located within a watershed to collect and hold runoff from surrounding fields. These ponds are used for irrigation, livestock water, recreational activities, and commercial fish production. Such bodies of water are often efficient traps for nutrients and sediments. For example, a small flood-detention reservoir in Missouri trapped 87 percent of the sediment, 71 percent of the phosphorus, and 37 percent of the inorganic nitrogen that entered it during a 3-year study (*105*).[2]

Section 208 of the Federal Water Pollution Control Act Amendments of 1972 (Public Law 92–500) requires that each State plan the management of area-wide water treatment. Any plan shall include "a process to (i) identify, if appropriate, agriculturally related non-point sources of pollution, including runoff from manure disposal areas, and from land used for livestock and crop production, and (ii) set forth procedures and methods (including land use requirements) to control to the extent feasible such sources." Because ponds collect runoff water, it is possible to control somewhat the quality of the water before it leaves the pond. In recent months there has been some interest in using farm ponds as a management tool in controlling nonpoint sources of pollution.

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[2] Italic numbers in parentheses refer to "References" at the end of this publication.

In the future, because of dwindling resources and increasing prices, nutrients will have to be utilized more efficiently in agricultural practices, including perhaps the recovery of nutrients that leave the fields in runoff and are trapped in farm ponds. Research is needed to determine the physical and biological limitations of the various methods for recovering those nutrients. This review considers some of the possible methods for nutrient recovery and some of the problems that limit each approach.

NUTRIENT RECOVERY FROM FARM PONDS

The concentrations of plant nutrients in farm ponds are considerably diluted, even though the sediments potentially represent a large reservoir of nutrients. In table 1, nutrient concentrations in some farm ponds are compared with nutrient concentrations in lakes and rivers. For the ponds, typical ionic micromolar concentrations (μM) are considered to be: phosphate (PO_4) phosphorus, 0.1 to 5; nitrate (NO_3) nitrogen, 5 to 100; ammonium (NH_4) nitrogen, 5 to 50; potassium, 50 to 500; calcium, 50 to 2,000; and magnesium, 50 to 2,000.

Nutrients can be recovered from ponds in the form of harvestable plant or animal material. One method might be the hydroponic culture of terrestrial or semiaquatic plants in the ponds. To assess the potential of this approach, it is necessary to know the nutrient-absorbing capabilities of various plants under different conditions.

NUTRIENT-UPTAKE CAPABILITIES

One major problem in the hydroponic culture of plants in ponds is the ability of the plants to extract sufficient nutrients from such a dilute supply. Another concern is the nutrient-uptake efficiency of cultured plants, compared to competing, unwanted plants. Nutrient-uptake capabilities have been estimated by comparing the nutrient-uptake kinetics of several species and groups of terrestrial and aquatic plants.

Nutrient-uptake kinetics

In 1936, Osterhout suggested that selective accumulation of ions by cells might be associated with specific substances in the cell membrane (*165*). Subsequently, the "carrier" hypothesis was expanded to account for certain features of ion transport, including the impermeability of the outer cell membrane to ions, the dependence on

Table 1.—Nutrients in natural waters

[Micromolar concentration (μM)]

Water source	Phosphate phosphorus	Nitrate nitrogen	Ammonium nitrogen	Potassium	Calcium	Magnesium	Reference
U.S. lakes	0.03–12	0.07–57	...	13–43	32–1,072	237–333	*185*
North American lakes and rivers	...	13–607	...	15–172	25–2,725	125–1,000	*6*, pp. 508–509
Prairie lakes of South Dakota	0.2–5.8	1.6–16	0–13	205–1,410	2,450–2,775	958–15,041	*101*
Farm ponds:							
Alabama	0.2–0.5	5–7	3.7–7	39–74	...	...	*39*
Colorado[1]	0.3–1.9	3.6–18	5.7–48	66–169	957–1,812	533–4,791	*23*
Illinois	5.8	15–86	...	...	...	...	*64*
Indiana	0.3–3.2	28–107	7–28	...	...	...	*166*
Minnesota	...	33–71	3–22	143–250	200–850	...	*5*
Missouri	0.3–0.5	52–110	13–15	...	...	...	*222*
North Dakota	...	71	...	205–461	525–2,350	33–2,166	*98*
Oklahoma	0.07–0.9	4.3–31	4–16	51–115	50–690	33–537	([2])

[1] Small lakes representative of shallow farm ponds on flat terrain.

[2] R. Davis, A. Olness, and W. Troeger, 1977, unpublished data, Water Management Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Durant, Okla.

cellular metabolism, and the selectivity of the ion transport (*78*). In experiments on the uptake of potassium by excised barley roots, Epstein and Hagen (*81*) treated the kinetics of ion transport in enzymological terms (*78*). An inorganic ion (or the organic substrate) binds to a carrier (or enzyme), and after transport of the ion (or substrate transformation), the carrier (or enzyme) is again free to react with another ion (or substrate molecule).

The rate of carrier-mediated ion transport, like the enzyme reaction rate, depends on two factors (*78*). One is the capacity factor, $V_{\max}$, the maximum rate achieved when all available carrier sites are loaded. The other is an intensity factor, Θ, the fraction of sites occupied at the ionic concentration $[S]$. The Langmuir adsorption isotherm gives

$$\Theta = \frac{[S]}{K_m + [S]}, \tag{1}$$

where K_m is the dissociation constant of the carrier-ion complex. If there is no counterflow of ions, the rate of absorption, V, is given by the product of the two factors Θ and $V_{\max}$,

$$V = \frac{V_{\max} \cdot [S]}{K_m + [S]}, \tag{2}$$

the Michaelis-Menten equation, which relates the rate of ion transport to ion concentration (or the rate of enzymic reaction to substrate concentration) (*78*).

The Michaelis-Menten equation can be rearranged in several ways to give straight-line plots, and the two most common ways (*65*) are the Lineweaver-Burk (*140*) and the Hofstee (*112*) methods. From such plots, the parameters K_m and $V_{\max}$ can be evaluated. K_m is the ion concentration at which the uptake rate is one-half of $V_{\max}$. Further, about 10 percent of $V_{\max}$ is achieved at an ion concentration equal to 0.1 K_m, and about 90 percent of $V_{\max}$ is achieved at 10 K_m (*160*).

With excised roots, Epstein and Hagen showed that ion uptake followed saturation kinetics in accordance with the Michaelis-Menten equation (*81*). Anomalies in the results became apparent when relatively high external ion concentrations were used (*34*). Detailed uptake curves over a wide range of concentrations yielded two isotherms, and the concept of the dual mechanism of ion uptake was developed (*77*). Mechanism I, represented by the first isotherm, operates up to about 1 m*M*. The second isotherm represents mechanism II, which functions above 1 m*M*. The high-concentration isotherm (mechanism II) can be separated into distinct phases, each having a hyperbolic pattern.

This dual pattern of ion uptake has been observed in a wide range of plant material, from excised roots to unicellular algae, and from belowground storage organs to leaf tissue. Experiments have involved a majority of the mineral elements essential for green plants (*79*, *80*). Mechanism I operates in the range of nutrient concentrations found in farm ponds. Isotherms for mechanism I, unlike those for mechanism II, are homogeneous (a smooth curve) and provide reliable K_m values.

For this review, the kinetic data for mechanism I seem to offer a convenient and meaningful way to compare the nutrient-absorbing capabilities of plants.

Literature since 1955 was reviewed to collect the kinetic data. Originally, we intended to use both the K_m and $V_{\max}$ values. However, the numerous methods used to report $V_{\max}$ have made it necessary to omit these data. Conversion of the heterogeneous information to a common base would distort the data.

The K_m values without corresponding $V_{\max}$ values may have merit. In comparisons of the two kinetic constants, the K_m seems to be a much more stable and conservative quantity. For example, the washing of excised or intact primary roots of corn seedlings in aerated distilled water, or in dilute salt solutions, doubled the uptake rate of phosphorus and potassium (*139*). The $V_{\max}$ values increased, but the values for K_m did not change. The K_m and $V_{\max}$ values for potassium uptake by excised barley roots were studied as a function of pretreatments to "load" the tissues to various degrees with potassium (*99*). The $V_{\max}$ values declined with increasing potassium in the medium, but the K_m values remained constant up to an external micromolar concentration of about 1,000. Further, no differences were observed when the K_m values for nitrate uptake by normal and by nitrogen-starved *Chlorella* cells were compared (*198*).

Nutrient uptake by phytoplankton generally follows Michaelis-Menten kinetics (*137*). Carpenter and Guillard have suggested that isolated strains of certain marine phytoplankton species,

Table 2.—Phosphate phosphorus uptake kinetics

Plant group or organism	Number of values	K_m (μM)			References
		Average	Median	Range	
Terrestrial angiosperms:					
Excised roots	25	3.9	3.5	0.7–8.0	*7, 41, 51, 52, 54, 66, 102, 103, 163, 202, 212*
Intact roots	9	6.1	3.6	0.6–20.7	*2, 53, 67, 70, 84, 118, 129*
Aquatic angiosperms:					
Excised roots	1	0.4	...	...	*97*
Intact plant	1	4.0	...	...	*97*
Foliage	7	11.4	0.3	0.01–39.0	*97, 126, 164, 187, 218*
Algae:					
Freshwater phytoplankton	23	2.5	0.8	0.1–16.0	*27, 56, 88, 97, 104, 119–121, 136, 137, 157, 180, 204, 209*
Freshwater filamentous	2	0.3	0.3	0.1–0.5	*97*
Marine phytoplankton	5	0.8	0.6	0.5–1.7	*96, 169, 199*
Hydrodictyon	1	70.0	...	...	*179*
Fungi: Yeast	6	79.5	10.0	2–400	*28–30, 100, 133*
Lichen	1	33.0	...	...	*89*
Bacteria (freshwater)	7	10.8	10.0	0.7–30.0	*55, 96, 106, 152*

termed "physiological races," are adapted to high or low nutrient levels and that these differences are reflected in the K_m values (*50*). Organisms from localities characteristically poor in nutrients generally have low K_m values and are therefore marked by an efficient nutrient-uptake system (*137*).

In summary, the choice of K_m values as a means of comparing the efficiency of nutrient uptake by plants from dilute solutions is justified. In some of the references, the K_m values themselves were not given but plots of the data were, and so established procedures (*188*) were used to calculate the K_m values from the plots. K_m values for mechanism I were selected from the available data because this mechanism operates in the range of concentrations encountered in farm ponds, and because mechanism I obeys Michaelis-Menten kinetics and is specific.

Comparison of K$_m$ *values for various plant groups.*—The K_m values for uptake of phosphate, sulfate, nitrate nitrogen, ammonium nitrogen, and potassium by various plants are compared in tables 2 through 6. The average values are summarized in table 7 and compared with the estimated typical levels of nutrients in ponds.

In table 2, the average K_m values for phosphate uptake are similar for terrestrial angiosperms, aquatic angiosperms, and freshwater phytoplankton, although the median K_m value for terrestrial angiosperms is significantly higher. Based on the averages and ranges, these groups of plants seem equally able to extract phosphorus from pond water. Yet with only 0.1 to 5.0 μM phosphate phosphorus expected in the water, the rates of uptake would be far from the maximum, and phosphorus is likely to be limiting, at least for the higher plants. Some algae can absorb and store phosphate from extremely dilute concentrations (see later). It is noteworthy that the marine phytoplankton have such a sensitive uptake mechanism for phosphate. This capacity correlates well with the high affinity they have for nitrate and ammonia. Levels of these nutrients are often low in the sea.

Data for sulfate uptake are scarce, but table 3 indicates that phytoplankton have a more efficient uptake system than terrestrial angiosperms.

K_m values for nitrate uptake in table 4 show the remarkably sensitive uptake mechanism of marine phytoplankton, with freshwater phytoplankton and terrestrial angiosperms following in order of decreasing sensitivity. Compared with the levels anticipated in the ponds, 5 to 100 μM nitrate nitrogen, the algae should be better able to compete for the supply. Nitrate is likely to be limiting for

Table 3.—Sulfate sulfur uptake kinetics

Plant group or organism	Number of values	K_m (μM) Average	Median	Range	References
Terrestrial angiosperms:					
Excised roots	18	38	20	6–180	*25, 47, 91, 113, 134, 161, 189, 212*
Leaf slices	1	8	...	...	*161*
Tissue culture	2	30	30	20–40	*191*
Aquatic angiosperms:					
Foliage	1	6	...	...	*126*
Algae:					
Freshwater phytoplankton	3	1	0.9	0.75–1.5	*210, 211*
Characeae (internodal cells)	1	60	...	...	*181*
Moss gametophyte	2	145	145	70–220	*146*
Fungus mycelium	1	10	...	...	*151*

Table 4.—Nitrate nitrogen uptake kinetics

Plant group or organism	Number of values	K_m (μM) Average	Median	Range	References
Terrestrial angiosperms:					
Excised roots	3	218	33	21–600	*94, 114, 147*
Intact roots	1	110	...	...	*176*
Tissue culture	1	400	...	...	*111*
Algae:					
Freshwater phytoplankton	3	55	15	3–148	*208, 215*
Marine phytoplankton	63	1.3	0.5	0.1–10.3	*26, 49, 50, 72, 73, 75, 76*
Bacteria (marine)	1	260	...	...	*44*

Table 5.—Ammonium nitrogen uptake kinetics

Plant group or organism	Number of values	K_m (μM) Average	Median	Range	References
Terrestrial angiosperms:					
Excised roots	2	18	18	17–20	*25, 94*
Intact roots	6	104	92	52–190	*108, 130*
Aquatic angiosperms:					
Foliage	2	180	180	44–316	*207*
Algae:					
Freshwater phytoplankton	3	0.5	0.15	0.14–1.2	*110, 208*
Marine phytoplankton	46	1.5	0.5	0.02–9.3	*26, 49, 60, 73–75*
Bacteria (marine)	1	260	...	...	*44*

Table 6.—Potassium uptake kinetics

Plant group or organism	Number of values	K_m (μM) Average	K_m (μM) Median	K_m (μM) Range	References
Terrestrial angiosperms:					
Excised roots	9	16	9	4–37	*17, 71, 78, 82, 99, 184*
Intact roots	2	15	15	3–27	*108, 128*
Leaf slices	4	77	41	27–200	*173, 174, 192*
Aquatic angiosperms:					
Intact plant	1	29	...	...	*221*
Foliage	1	94	...	...	*124, 125*
Algae: Freshwater phytoplankton	2	125	125	70–180	*18, 21*
Liverwort gametophyte	2	223	223	87–360	*122*
Moss gametophyte	2	470	470	440–500	*146*
Fungus mycelium	1	11,800	...	...	*190*
Fungi: Yeast	1	500	...	...	*10*

Table 7.—Summary of nutrient-uptake kinetics

Plant group or organism	Average K_m (μM) NO_3 N	NH_4 N	PO_4 P	SO_4 S	K
Terrestrial angiosperms:					
Excised roots	218	18	3.9	38	16
Intact roots	110	104	6.1	...	15
Leaf slices	...	...	...	8	77
Tissue culture	400	...	...	30	...
Aquatic angiosperms:					
Excised roots	...	...	0.4	...	...
Intact plant	...	...	4.0	...	29
Foliage	...	180	11.4	6	94
Algae:					
Freshwater phytoplankton	55	0.5	2.5	1	125
Freshwater filamentous	...	...	0.3	...	...
Marine phytoplankton	1.3	1.5	0.8	...	...
Hydrodictyon	...	...	70.0	...	...
Characeae (internodal cells)	...	...	...	60	...
Liverwort gametophyte	...	...	...	...	223
Moss gametophyte	...	...	...	145	470
Lichen	...	...	33.0	...	...
Bacteria:					
Freshwater	...	...	10.8	...	...
Marine	260	260	...	...	...
Fungus mycelium	...	...	...	10	11,800
Fungi: Yeast	...	...	79.5	...	500
Nutrient levels available in farm ponds (from table 1)	5–100	5–50	0.1–5	...	50–500

the higher plants. These same general relationships seem to hold for ammonium nitrogen (table 5).

The situation is reversed for potassium. The K_m values in table 6 show that terrestrial angiosperms have a distinct advantage in the uptake of potassium, compared with phytoplankton and aquatic angiosperms. The levels of potassium expected in ponds, 50 to 500 μM, should provide an adequate supply for the higher plants and may be sufficient for other groups. Potassium may be limiting for aquatic macrophytes in some lakes (*97*).

In summary, terrestrial angiosperms, compared with algae and aquatic angiosperms, can compete for phosphate but may be limited by the levels available in ponds. The terrestrial angiosperms are at a disadvantage for both nitrate and ammonium uptake and may be similarly limited in ponds. The terrestrial plants have an advantage in the absorption of potassium.

Significance of C_0.—A parameter related to uptake kinetics is C_0, the lowest nutrient concentration to which plants can deplete the solution, Or, C_0 is the concentration at which net influx equals zero, where influx equals efflux. C_0 suggests how well some plants might compete for nutrients in dilute solutions such as ponds.

Phosphate C_0 values for several crop plants ranged from 0.043 to 0.30 μM (*70*, *131*, *132*). For nitrate, values were from 1.4 to 4.0 μM (*69*, *217*). A comparison of these values with the range of nutrient concentrations expected in ponds indicates that terrestrial plants should be able to extract phosphate and nitrate from the waters.

Direct tests for competition

The above discussion has focused on nutrient-uptake kinetics as a means of estimating the abilities of groups of plants to compete for nutrients in ponds. Although data were not available for terrestrial angiosperms, competition experiments have been conducted with macrophytes and algae grown together in the same culture flask with adequate supplies of all essential elements except one.

For these mixed cultures the organisms were: two macrophytes, *Elodea occidentalis* and *Myriophyllum spicatum;* and a filamentous alga, *Draparnaldia plumosa* (*97*). The limiting nutrient was about 50 percent of the amount required to maintain the critical concentration in the expected plant yield. Competition was judged by (1) the percentage of the total yield represented by each species and (2) the proportion of growth represented by each with adequate and with less than adequate amounts of a limiting nutrient.

For *Elodea* and *Draparnaldia* grown together (*97*), little difference was noted in the efficiency of nitrate nitrogen utilization, as judged by the above criteria. *Draparnaldia* was superior in competing for phosphate but was ineffective in competing for potassium. *Elodea* was ineffective in competing for calcium, but growth of the two plants was about equal at limiting concentrations of magnesium. The K_m values (mechanism I) indicated that *Draparnaldia* should be more efficient than *Elodea* in phosphate uptake, and this was confirmed by the culture.

Experiments were also conducted with the two macrophytes plus the alga (*97*). With limited phosphorus, the competitive capacities were *Draparnaldia* greater than *Myriophyllum* greater than *Elodea*, as expected. With low potassium, *Draparnaldia* was least successful, and *Myriophyllum* somewhat more successful than *Elodea*.

Although uptake kinetics can often predict successful competition for nutrients in mixed cultures, the authors of that study (*97*) concluded that until more information is available, a procedure using plant yield should be favored in determining effectiveness of competition for nutrients.

NUTRIENT REQUIREMENTS FOR MAXIMUM GROWTH

Another approach to estimating the success that terrestrial angiosperms might have in extracting nutrients from eutrophic ponds is to compare yields of plants grown in a nutrient solution.

Terrestrial angiosperms

The nutrient-solution concentrations needed for maximum growth reflect the complex interactions of various uptake efficiencies, translocation patterns, tissue requirements as related to the critical nutrient concentration, and nutrient mobilities. The critical nutrient concentration is the minimum concentration of nutrient present in the plant that permits maximum growth (*142*). Plants with a high tissue requirement may have a low requirement for nutrient levels in the culture solution, provided that they have a high nutrient-absorption rate.

Some examples of nutrient concentrations needed in solution culture for maximum growth are given in table 8 and are summarized and com-

Table 8.—Nutrient concentrations required for plant growth in solution culture, by plant

Plant	Nutrient concentrations (μM) for—			References
	Poor growth[1]	Moderate growth[2]	Maximum growth	
PHOSPHATE PHOSPHORUS				
Barley	...	...	7	*3*
Corn	...	2–3	0.7–5	*3, 167, 203*
Groundnut	...	...	20	*2*
Onion	1	...	10	*41*
Potato	1	...	16	*116*
Rape	...	...	10	*42*
Rice	...	...	2–25	*2, 85, 200*
Sorghum	...	2	5	*203*
Soybean	...	...	5	*167*
Tomato	2	...	5	*203*
Two pasture species	...	...	24	*143*
Various annual pasture species	0.04–0.2	0.2–2	1–25	*11*
NITRATE NITROGEN				
Wheat	10	25	70–140	*61, 114*
AMMONIUM NITROGEN				
Wheat	...	10	30	*61*
POTASSIUM				
Barley	0.25	2.5	25	*220*
Cabbage	...	...	130	*92*
Crop and pasture species	...	...	24–100	*12*
Red beet	...	...	150	*92*
Rice	...	...	256	*86*
Sweet vernal grass (acidic soil clone)	...	...	230	*63*
Sweet vernal grass (calcareous soil clone)	230	...	...	*63*
CALCIUM				
Cotton (excised root culture)	...	...	200	*127*
Festuca	...	...	20–100	*193*
Grasses, cereals, and legumes	...	2.5–10	2.5–1,000	*144*
Rice	...	...	250	*85*
MAGNESIUM				
Corn inbred B57	31	...	120	*59*
Corn inbred Oh40B	1,200	...	4,100	*59*
Groundnut	...	...	40	*83*
Rice	...	...	33	*85*
Sweet vernal grass (acidic soil clone)	...	...	370	*63*
Sweet vernal grass (calcareous soil clone)	...	...	370	*63*

[1] Yield reduced 80 percent.

[2] Yield reduced 50 percent.

Table 9.—Nutrient concentrations required for plant growth in solution culture, by nutrient

Nutrient	Nutrient concentrations (μM) for—			Concentrations in ponds[3] (μM)
	Poor growth[1]	Moderate growth[2]	Maximum growth	
Nitrate nitrogen	10	25	70–140	5–100
Ammonium nitrogen	...	10	30	5–50
Phosphate phosphorus	0.04–2	0.2–3	0.7–25	0.1–5
Potassium	0.25–230	2.5	24–256	50–500
Calcium	...	2.5–10	2.5–1,000	50–2,000
Magnesium	31–1,200	...	33–4,100	50–2,000

[1] Yield reduced 80 percent. [2] Yield reduced 50 percent. [3] From table 1.

pared with available levels of nutrients in ponds in table 9.

These data suggest several conclusions. Most species should grow only poorly to moderately on the phosphate concentrations in ponds. This conclusion correlates well with a similar one reached earlier, based on uptake kinetics. The nitrate levels in ponds should support only poor to moderate growth of some terrestrial plants. Some plants will not be limited by the concentrations of potassium, calcium, and magnesium.

Phytoplankton

A key question in considering the feasibility of hydroponic culture of plants in ponds is: Can higher plants reduce nutrient concentrations sufficiently to eliminate nuisance algal blooms?

Both growth and nutrient uptake by algae (and other micro-organisms) as a function of concentration follow saturation kinetics. The Michaelis-Menten equation can be used to describe the relationship between nutrient concentration and both growth and nutrient uptake (*104*). The equation results in a maximum rate and half-saturation constant for growth and a corresponding maximum rate and half-saturation constant for nutrient uptake.

A comparison of half-saturation constants for nutrient uptake will indicate the various abilities to extract nutrients, but equal or similar half-saturation constants for uptake do not necessarily indicate equal growth responses (*205*). For example, the phosphorus requirements for two freshwater diatoms were compared (*204*). The saturation constants for uptake were essentially the same for *Asterionella formosa* and *Cyclotella meneghiniana*. However, the half-saturation constant for growth was more than six times greater for *C. meneghiniana* (0.25 μM) than for *A. formosa* (0.04 μM), indicating that *A. formosa* is better able to grow at low phosphate concentrations.

With phosphate limited, the half-saturation constant for growth of *Selenastrum capricornutum* varied from 0.12 μM to 0.18 μM (*206*). Because the maximum specific growth rate is 1.85/day (or 2.67 doublings per day), the low concentrations of phosphorus found in many natural waters could support the growth of this organism at rates between 0.9 and 1.8/day (or between 1.3 and 2.6 doublings per day). Other examples of half-saturation constants for phytoplankton growth with phosphate limited are 0.03 μM for *Cyclotella nana;* 0.032 μM for *Thalassiosira fluviatilis;* and 48 μM for *Scenedesmus obliquus* (*195*). For *Nitzschia actinastroides,* a freshwater diatom, the half-saturation constant for phosphate limited growth ranged from 0.013 μM to 0.014 μM (*157*).

In summary, the half-saturation constant for growth limited by phosphate is in the range below 0.16 μM for nearly all algae examined so far, and sometimes it is below 0.03 μM (*95*). With phosphate limited, the concentrations expected in farm ponds should support the growth of several species of phytoplankton at near maximum rates.

Additional information on the nutrient concentrations at which nuisance blooms might develop may be obtained by comparing the cell quotas for various algae. The cell quota, or minimum nutrient concentration per cell, is the cell content at which cell division stops. The limiting phosphorus per cell for *Asterionella formosa,* for example, is a small amount, about 6×10^{-8} μg P/cell (*149*). For this alga, at an initial concentration of 0.03 μM (1 μg P/l) in the medium, a population of some

16×10^{6} cells/l can be produced before phosphorus becomes limiting. Furthermore, this diatom can take up and store phosphorus in reserve from concentrations less than those found in some phosphorus-poor lakes, that is, below 0.03 μM (*149*).

Values for the minimum phosphorus per cell for other species of phytoplankton range from 5×10^{-8} to 10×10^{-8} μg/cell (*4, 182, 194, 195*). It is unlikely that terrestrial plants in a hydroponic culture can extract enough phosphorus from ponds to eliminate phytoplankton blooms.

EXTERNAL FACTORS AFFECTING NUTRIENT UPTAKE

Stirring.—Because of an unstirred layer near the surface of the nutrient absorption site, diffusion may limit the rate of ion uptake from dilute solutions (*162*). In addition, for continuous flow experiments at low concentrations, it is critical to provide high flow rates to prevent depletion (*68*). The literature contains many references to the importance of stirring for nutrient uptake from dilute solutions (*16, 57*), and several examples are given in table 10.

Equations have been developed for the rate of nutrient absorption by aquatic plants approximating the shapes of spheres, disks, cylinders, and plates (*159*). These equations show that absorption by attached plants is aided by a current, and absorption by phytoplankton by a rapid sinking rate. Transport limitation of nitrate uptake was demonstrated experimentally at low nutrient concentrations in a quiescent medium for a marine diatom (*168*). The effect of transport limitation was decreased by mixing and was eliminated completely in a medium being sheared at a high rate, or in a medium of sufficient concentration.

Adequate stirring is one of the most critical factors requiring proper management in a hydroponic culture of plants in ponds. A related problem is the effect of stirring on the nutrient-buffering capacity of the water column.

Transpiration.—In a dilute solution, transpiration had no effect on the uptake of potassium, calcium, nitrate nitrogen, or sulfate sulfur by sunflower plants (*33*). Similar results were obtained with wheat absorbing phosphate (*31*) and with barley seedlings taking up nitrate (*176*).

When the external concentration and the nutrient status of the plants are sufficiently low, wide variations in the rate of transpiration have little effect on the transfer of nutrients to the shoots. However, when the concentration and nutrient status are high, the rate of transfer of ions to shoots may vary closely with the rate of transpiration (*183*).

Oxygen.—In the absence of oxygen, the metabolic component of salt absorption is inhibited in aerobic organisms (*197*). Experiments were conducted with excised barley roots in phosphate solutions in equilibrium with nitrogen, oxygen gas mixtures containing oxygen at partial pressures ranging from 0.002 to 21 percent oxygen. With the total gas pressure kept at 1 atmosphere, the curve for phosphate uptake against oxygen tension was hyperbolic over the range 0 to 3 percent, with 0.3 percent giving half the maximum rate (*115*). Uptake was independent of the oxygen partial pressure above 3 percent.

The experiments were conducted at 30° C. At this temperature, 3 percent partial pressure of oxygen would provide 14 percent of the saturation value in water against air, or 1 mg/l in solution. At 0.3 percent oxygen, the solution value would be

Table 10.—Effects of stirring or flow rate on nutrient uptake and growth

Plant	Nutrient[1]	Action	Effect	Reference
Annual pasture species	P	Increased flow	Stimulated growth	*13*
Marine diatoms	P	do	Increased uptake	*48*
Wheat, peas, beans, corn	NO_3 N, NH_4 N	do	Depletion prevented	*68*
Clover	K	do	Stimulated growth	*1*
Rice	Mg	do	Increased uptake	*87*
Freshwater algae	P	Create current flow	do	*186*
Freshwater algae (*Oedogonium*).	P	do	do	*219*
Marine diatoms	NO_3 N	Stirring	do	*168*
Excised barley roots, disks of red beets, and potatoes.	K (Rb)	do	do	*171*

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[1] Concentration of all nutrients was less than 1 m*M*.

0.1 mg/l. Data from farm ponds and from model ponds indicate that the surface waters rarely go below 1 to 2 mg/l oxygen (*64*, and O. R. Lehman, 1977, unpublished data). Therefore oxygen should not be a limiting factor for nutrient uptake by plants growing hydroponically in the pond surface, especially if the water is stirred to avoid nutrient depletion.

Temperature.—Salt absorption by plants increases with rising temperature until a maximum rate is reached, and then the rate decreases at still higher temperatures (*197*). For example, the rate of phosphate absorption by barley plants increases linearly with temperature from 0° to 40° C (*145*). At temperatures above 40° C, absorption is progressively reduced in many plants, presumably because of the gradual inactivation of the enzyme systems involved (*197*).

Within the physiological range, increased temperature raises V_{max} for uptake. However, K_m also increases; the affinity is reduced at higher temperatures. Examples include phosphate uptake by excised corn roots (*54*) and by excised roots of various other species (*51*). Whether the increase in V_{max} can be expected to compensate for the increase in K_m is moot. Temperature will not likely be a factor requiring management in the pond culture system.

Hydrogen ion concentration (pH).—The pH of lake waters varies from as low as 1.7 in some volcanic lakes containing free sulfuric acid, to 12.0 or more in some closed alkaline lakes rich in soda (*117*, p. 690). The usual pH range is between 6.0 and 9.0. Seepage lakes and all lakes in regions of igneous rock tend to have values below 7.0. Only calcareous waters have values well over 8.0. Data from some farm ponds show an overall pH range of 5.6 to 8.8 (*5*, *23*, *98*, and W. Troeger, 1977, unpublished data).

The pH of the ambient solution markedly affects both the cation and anion absorption by roots (*155*) and by other plant tissues and cells (*197*). For short-term experiments with excised roots, the maximum absorption rate occurs at pH 5 to 7 (*155*). For excised barley roots, the physiological range for cation uptake is pH 4 to 9 (*175*). Cation uptake is reduced below pH 5 by a combination of the competitive effects of hydrogen ion and by damage resulting from excessive acidity (*155*, *175*). Examples include uptake of rubidium and strontium by excised barley roots (*93*), potassium uptake by excised barley roots (*90*, *93*), calcium uptake by excised corn roots (*148*), and potassium uptake by excised vetch roots (*213*).

Calcium and other polyvalent cations apparently play a crucial role in maintaining the integrity of the absorption process, especially in the acidic pH range (*155*, *175*). Damage from a low pH in the absence of calcium seems to be partially reversible by adding calcium.

Anion uptake is less affected below pH 5 but is strongly reduced at a high pH, primarily by hydroxyl and bicarbonate ion competition (*155*, *157*). Thus, nitrate uptake by barley seedlings was greater at a low pH and decreased as the pH increased (*176*). Similarly, nitrate uptake by corn seedlings steadily decreased from pH 5 up to pH 8 (*114*). The amount of nitrate absorbed from solutions freed of bicarbonate ions was independent of the pH at values between 4 and 9 (*197*).

Some data indicate that for anion uptake, a rise in pH does not affect V_{max} but does increase K_m (lower affinity). This condition was found for borate uptake by sugarcane leaf slices (*32*) and for phosphate uptake by excised barley roots (*102*, *135*).

The pH of the medium has an especially important effect on phosphate absorption, because over the physiological range of pH values the predominant ionic form shifts from $H_2PO_4^-$ to $HPO_4^=$ and finally to $PO_4^{\equiv}$, as the medium becomes more alkaline (*197*). The effects of pH on phosphate uptake have been explained in terms of the differential rates of absorption and relative concentrations of univalent and bivalent ions in solution (*102*). Sutcliffe (*197*) suggested that only $H_2PO_4^-$ is absorbed to an appreciable extent.

The pattern for blue-green algae seems to contrast with the above. For example, phosphate uptake by *Anabaena variabilis* showed a broad maximum at pH 7.5 to 9.0 (*109*). Further, the optimum pH for ammonium uptake by *Pseudanabaena catenata* was 9 or higher, and the pH for phosphate was similar (*110*). In contrast, a green alga, *Scenedesmus quadricauda*, had an optimum pH for ammonium uptake of 6 to 7; and for *Ankistrodesmus braunii* the optimum pH for phosphate was 6 to 7. These differences may provide some understanding for the observation that green algae are able to replace blue-green algae at a low pH (*110*).

In summary, the data indicate that some farm ponds may have a slightly alkaline pH. This condition may create a pH management problem because the optimum pH for phosphate uptake and nitrate uptake by higher plants is below 7. A high pond pH would also tend to favor the development of blue-green algae, perhaps in bloom proportions.

Light.—For submersed green plants, visible light stimulates ion uptake, as first shown by Hoagland (*123*). Examples include the uptake of potassium by algae (*19*, *20*, *214*), aquatic macrophytes (*124*), and corn leaf slices (*172*, *173*); and the absorption of chloride by algae (*19*) and aquatic macrophytes (*8*, *9*). Light supplies energy for ion uptake in green plants by means of photosynthesis (*197*); but more directly it seems that uptake of both cations and anions is linked to ATP produced by photophosphorylation (*123*).

The relationship is more complicated when the effect of light on the uptake of a metabolized solute is considered, whether phosphate, nitrate, or bicarbonate, or neutral molecules such as carbon dioxide and sugars (*178*). It is often difficult to distinguish the effects of light on the uptake of the metabolite from light effects on its subsequent metabolism. For example, illumination increased the capacity of barley to absorb nitrate, possibly because of an increased energy supply and increased nitrate reductase activity (*177*). Nitrate reduction in most algae is light stimulated, and it seems that a feedback control restricts the rate of nitrate entry to the rate at which it is reduced. The characteristics of the light stimulation of nitrate uptake are the same as for nitrate reduction. Therefore, any intrinsic light effects on the uptake mechanism itself are obscured by the feedback mechanism (*178*).

For terrestrial angiosperms in a hydroponic pond culture, the primary effect of light would be as an energy source to drive indirectly the ion absorption process in the roots. Opportunities for manipulation seem to be minimal.

UTILIZATION OF AQUATIC WEEDS

Another way to recover nutrients from ponds is to harvest and utilize directly the aquatic weeds that naturally populate many such ponds. Even though the nutrient concentrations in the waters may be low, the levels are often adequate to support the growth of nuisance aquatic plants and algal blooms. Excessive populations of water weeds interfere with boating and irrigation, create stagnant and noxious conditions, and shelter and promote the development of disease-vector animals (*153*).

Prospects for harvesting and converting a portion of the world's wealth of aquatic weeds into some useful material are currently of broad interest (*156*, *159*). Table 11 summarizes some of the possible uses for harvested aquatic weeds. The range is large, and people are increasingly recognizing the need to manage aquatic plants rather than eradicate them with herbicides (*24*, *37*, *159*). For example, protein concentrates from green plant leaves have a high nutritive value (*196*), and leaf protein has been extracted from water hyacinths. However, the yield was only about 33 percent of the crude protein content, compared with 50 to 80 percent yields of crude protein from legume leaves (*201*). Again, some aquatic plants, on a dry-weight basis, may contain as much or more crude protein, crude fat, and mineral matter as conventional forage crops (*35*). Yet, most water weeds contain only one-quarter to one-half as much dry matter as forages, and drying is expensive.

Thus, a chief problem is the efficient harvest of large amounts of plant material comprised mostly of water (up to 97 percent) and transporting it to a processing facility (*24*). For these reasons, aquatic plants will probably not have much direct economic value in the near future (*35*). Further, some byproducts from harvested aquatic plants may have little cash value (*150*).

Finally, the addition of nitrogen, phosphorus, and potassium greatly stimulated the growth of water hyacinths in ponds (*40*). Thus, nutrients—contrary to the purpose of growing plants to recover nutrients already in the water—might have to be added in some instances to produce enough yield to support a harvest.

Table 11.—Possible uses for harvested aquatic weeds

Use	References
Compost	*24, 38, 107, 141, 150, 159*
Fertilizer	*38, 141, 154, 159*
Fiber for paper and paper products	*24, 38, 156, 159*
Fodder	*24, 38, 62, 107, 141, 150, 159*
Leaf protein extract for food	*24, 36, 37, 141, 159, 170*
Mulch	*38, 141, 159*
Rhizome starch for food	*22, 58, 156*
Soil amendment	*24, 150, 159*
Woven products	*38, 156, 159*
Xanthophyll and protein for poultry	*14, 45*

Fish and other animals

Another means of recovering nutrients is to harvest some of the fish, also a possible way to slow or reverse eutrophication (*46*). Four species of fish (carp, northern squawfish, largescale sucker, and rainbow trout) were harvested from temperate lakes, and nutrient removals were calculated. Less than 1 percent of the phosphorus and nitrogen entering the lakes would be removed, if the maximum annual yield of fish were harvested.

As a biological weed-control agent, rather than as a method for recovering nutrients, the herbivorous white amur (grass carp) has been released into several Arkansas lakes (*15*). This fish has effectively controlled such weeds as *Elodea*, *Myriophyllum*, *Potamogeton*, and *Najas* and is reported not to strip lakes of all plant cover. Upright, emergent swamp grasses, reeds, and lilies are not eaten. The fish has been widely accepted as a commercial food fish.

Similar experiments with grass carp to control aquatic weeds are being conducted in Florida (*216*). However, desirable aquatic plants may also be destroyed, reducing littoral vegetation vital to the life cycle of fish and fish-food organisms. Further, the digestive tract of the fish is short, and so about one-half of its food passes through undigested. The grass carp feces promote heavy plankton production, and the types of fish that respond to the high amounts of plankton may be undesirable (*216*). Other possibilities for producing a crop from the biological control of aquatic weeds include ducks, geese, and swans, crawfish, and nutria (*159*). Monocultures of fish and other animals may offer more promise as biological weed-control agents than as a means of recovering nutrients.

Algae

The harvesting and utilization of algae is another possible means of nutrient recovery from eutrophic ponds. Culturing freshwater algae for food is a speculative venture (*22*). However, *Spirulina* is a traditional food in parts of the Chad Republic. This edible blue-green alga is collected from oases and sold in the form of cakes (*159, 170*). The organism can be 45 to 65 percent protein on a dry-weight basis, and it could be used to improve protein-deficient diets in that area (*138*). *Spirulina* might also have promise as an animal feed. Another blue-green alga, *Nostoc*, is reported to be cultivated and eaten in central Asia and in China (*43*).

Some of the nutrients in eutrophic ponds could be used to support the growth of nitrogen-fixing blue-green algae as a means of producing a green manure for agricultural use. Problems here are similar to those for growing algae for food: (1) the maintenance of a desirable monoculture of algae, (2) harvesting and handling the algal mass, and (3) the possible need to add to—rather than removing—the nutrients already in the ponds in order to sustain a satisfactory production level.

SUMMARY AND CONCLUSIONS

Several approaches for recovering nutrients from eutrophic farm ponds were considered, including growing terrestrial or semiaquatic plants in hydroponic culture in the ponds, direct utilization of aquatic weeds, and the use of a monoculture such as fish (and other animals) or algae. Most of the review focused on the feasibility of culturing plants in a hydroponic system in ponds as a means of recovering nutrients in the form of a high cash-value crop. Emphasis was placed on various aspects of the competition for nutrients and on comparative yields of plants in dilute culture solution.

HYDROPONIC CULTURE OF PLANTS

Competition for nutrients

The half-saturation constant K_m is a valid way to compare the potential efficiencies of nutrient uptake by different species and groups of plants. The K_m values for uptake of several nutrients by various plants were compared with available nutrient levels in ponds. Terrestrial angiosperms seem able to compete about equally for phosphate, but the supply of this nutrient is likely to be limiting. They would not be expected to compete with phytoplankton for nitrate, and this nutrient is also likely to be limiting. The terrestrial angiosperms seem to have the advantage for uptake of potassium from the ponds.

The parameter C_0 (concentration where net influx equals zero) was used to indicate how well some plants might compete for nutrients. These data suggest that terrestrial plants would be reasonably able to extract phosphate, nitrate, and potassium from the levels expected in ponds.

Several external factors affecting nutrient uptake were explored. Because of the dilute concentrations of nutrients in the ponds, stirring of the water is a critical factor requiring proper management. Alkaline pH lessens the uptake of nitrate and phosphate. Transpiration, temperature, oxygen, and light pose no potential problems.

Plant yields in dilute solution

The nutrient concentrations needed for maximum growth of terrestrial plants were compared. Phosphate supplies in ponds would support only poor to moderate growth; nitrate levels would support only poor to moderate growth; and potassium, calcium, and magnesium would probably not be limiting.

The half-saturation constants for growth of phosphate-limited phytoplankton were compared with pond concentrations. The growth of several species of phytoplankton would be supported at near maximum rates. Information on the phosphate cell quota for various algae was compared. These values, the cell content at which cell division stops, indicate that terrestrial plants in pond culture would not likely be able to extract enough phosphate from ponds to eliminate phytoplankton blooms.

Other Means of Nutrient Recovery

The direct utilization of aquatic weeds will have little potential in the near future because of the high costs of harvesting and drying, probable low cash value of byproducts, and possible need to add nutrients to ponds to sustain the production required for a profitable harvest.

The harvest of fish is not an efficient method of nutrient removal from ponds. Even though certain herbivorous fish have been accepted as a commercial food fish, the use of fish as a biological weed-control agent needs more research, because of possible destruction of vital littoral vegetation and because of possible indirect effects on plankton production and on other kinds of fish.

Certain blue-green algae growing in lakes or ponds are utilized as a high-protein food in some areas of the world. Also, nitrogen-fixing blue-green algae could be cultured in ponds and harvested for use as a green manure in agricultural fertilization. Any such schemes to maintain an algal monoculture will face common problems: (1) keeping the desired alga in culture, (2) efficiently harvesting and handling it, and (3) maintaining a sufficient nutrient supply to support production.

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